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An Investigation into Recommendations of NZSEE for Seismic Assessment of Steel Moment Resisting Frames

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Abstract

The major guidance documents for seismic assessment of existing buildings are ASCE 41-06 in US, Eurocode 8 Part 3 in Europe and NZSEE recommendations in New Zealand. All of these guidelines have proposed using nonlinear static analysis as a tool for seismic assessment of buildings. In New Zealand recommendations there is a parameter %NBS which means percentage of new building standard, the building with %NBS=100 is a building that satisfies standards of a new building. NZSEE recommendations have proposed force based, displacement based and consolidated force / displacement based methods for seismic assessment of existing buildings. Consolidated force / displacement based method is a combination of force based and displacement based methods. Displacement based method has a direct emphasis on estimating the ultimate displacement capacity of the structure and utilizes displacement spectra which can represent the characteristics of earthquakes. In this paper 5 and 10 story steel moment resisting frames are designed with %NBS approximately equal to 100 calculated via displacement based method. In this method the nonlinear static analysis is used for estimating strength and deformation capacity of steel moment resisting frames then nonlinear dynamic analysis procedure is used to assess the seismic performance of these structures according to ASCE 41-06.

Keywords: Nonlinear Static Analysis; Steel Moment Resisting Frame; Nonlinear Dynamic Analysis; Displacement Based Method; Life Safety

1. INTRODUCTION

Force based and displacement based approaches are allowed for seismic assessment of existing buildings in NZSEE recommendations (2006). In both methods the probable collapse mechanism and its lateral strength and displacement capacity should be calculated. Probable collapse mechanism can be calculated by simple lateral mechanism analysis (SLaMA) or by nonlinear pushover analysis which is a refinement of the SLaMA approach. In displacement based method the behavior of the system is considered to be that of an equivalent single degree of freedom system. Expected displacement demand is based on the structure characteristics (effective stiffness and equivalent viscous damping) at maximum

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displacement capacity rather than initial elastic characteristics. Displacement based methods place a direct emphasis on establishing the ultimate displacement capacity of lateral force resisting system. In this paper displacement based method is used for design of steel moment resisting frames. This paper presents the seismic evaluation of two steel moment frames with different number of stories (5 and 10 story) designed such that their %NBS be approximately equal to 100 in accordance with NZSEE recommendations, by using nonlinear dynamic analysis procedure in ASCE 41-06 (2007). Nonlinear analyses and performance evaluations are performed by program Perform-3D (2006).

2. DISPLACEMENT BASED METHOD

In displacement based method determination of base shear capacity of structure V_{prob}, and displacement capacity of structure U_{sc} is required. U_{sc} is the sum of elastic and inelastic displacements, $U_{sc} = U_{el} + U_{inel}$. U_{sc} and U_{el} can be approximated as the lateral deflection at an effective height, h_{eff} of the structure. Determination of h_{eff} is reliant on a good knowledge / understanding of the elastic and inelastic behavior of the structure and is not readily amenable to simple calculations once the structure is no longer elastic. For the elastic case U_{el} is the top story displacement divided by the modal participation factor of the first mode. If little more is known about the particular characteristics of the structure under consideration, and there are no column mechanisms, it is considered reasonable to use the same factor to approximate inelastic behavior. In this paper U_{sc} is calculated by dividing the top story displacement to the modal participation factor of the first mode Γ. For calculation of structure base shear capacity, and structure displacement capacity U_{sc} the following steps should be performed.

- Determine the probable flexural strengths of the critical sections of the members
- Determine member plastic rotation capacities
- Determine the post-elastic deformation mechanism of the structure that is likely to occur during seismic loading and hence the probable horizontal base shear capacity, V_{prob}, of the structure. The post-elastic mechanisms can be investigated using nonlinear pushover analysis
- Calculate the structure displacement capacity U_{sc} based on member plastic rotation capacities, and check if interstory drifts are less than 2.5 percent interstory drift limit which is determined by New Zealand standard for earthquake actions (2004) in the displacement capacity of structure.

In displacement based method the spectral displacement demand of the structure at height h_{eff} should be determined. For this purpose effective stiffness, effective period and ductility should be determined for the equivalent single degree of freedom model of the structure (substitute structure). After determination of base shear capacity of structure and displacement capacity of structure U_{sc}, the effective stiffness, effective period and ductility of structure can be calculated from the following equations.

$$k_{eff} = \frac{V_{prob}}{U_{sc}} \tag{1}$$

$$T_{eff} = 2\pi \sqrt{\frac{W_t}{g\, k_{eff}}} \tag{2}$$

$$\mu = \frac{U_{sc}}{U_{el}} \tag{3}$$

W_t is total seismic weight of structure and g is the acceleration of gravity. After calculation of structural ductility μ, the equivalent viscous damping of the structure should be calculated based on the value of structural ductility. In this paper equation (4) proposed by Priestley (2007) is used for calculation of equivalent viscous damping.

$$\xi = 0.05 + 0.577\left(\frac{\mu - 1}{\pi\mu}\right) \tag{4}$$

Based on New Zealand standard for earthquake actions (2004) the structural performance factor S_P, should be calculated by the following equation.

If $1 < \mu < 2 \qquad S_P = 0.7$ (5)

Otherwise $\qquad S_P = 1.3 - 0.3\mu$

In displacement based method a displacement response spectrum $\delta(T)$ is required, that can be calculated from the 5%-damped elastic acceleration spectrum $C(T)$ using the following equation.

$$\delta(T) = 9.81C(T)T^2 / 4\pi^2 \tag{6}$$

Displacement spectra for different damping values may be obtained by multiplying $\delta(T)$ for 5% damping by the factor K_ξ.

$$K_\xi = [7/(2+\xi)]^{1/2} \tag{7}$$

Where ξ is the equivalent viscous damping.

The spectral displacement demand of the structure at height h_{eff}, can be calculated by the following equation

$$U_{sd} = \delta(T_{eff})K_\xi \tag{8}$$

$$If\ \frac{U_{sc}}{S_p U_{sd}} = 1 \Rightarrow \%NBS = 100 \tag{9}$$

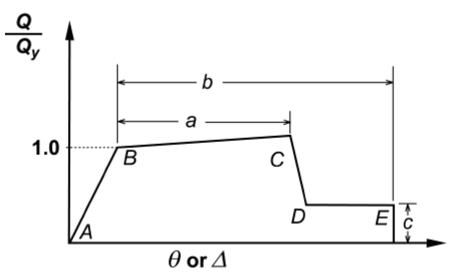

Figure 1: Generalized Force-Deformation Relation for Steel Elements

3. MODELING

2 dimensional mathematical models were chosen for analyses. The force-deformation curve of each member was modeled in according to ASCE 41-06 (2007) suggestions. For definition of nonlinear hinges

in columns the interaction of axial force and bending moment was considered and nonlinear behavior was modeled by $P-M$ hinges at both ends of columns. In modeling of force-deformation curves the post yield slope was assumed equal to 3% and strength loss was also considered. Generalized force-deformation relation of beams and columns is shown in figure 1.

4. DESIGNED STRUCTURES

In this paper we have tried to use the displacement based method proposed in NZSEE recommendations, to design typical structures with %NBS equal to 100. These buildings assumed to be located in very high seismic risk area based on Iranian seismic code (2005) and soil type II (average shear wave velocity would be 360-760 m/s), therefore 5%-damped elastic spectrum of Iranian seismic code for soil type II was used in calculations. To evaluate the performance of typical structures that satisfy %NBS equal to 100 in displacement based method, two low and medium rise (5 and 10 story) steel moment resisting frames were designed. The properties of steel material which was used in models is consistent with properties of steel which is common in Iran (yield stress, F_y=2400 Kg/cm^2 and modulus of elasticity, E=2.1×10^6 Kg/cm^2). The expected value of steel yield stress F_{ye}=2640 Kg/cm^2 was used for modeling of beam and column hinges. The structures were considered to have 4 bays with the bay length equal to 4 m. The story height of the frames was 3.2 m. Gravity loads were supposed to be similar to common loads of residential buildings in Iran. The dead loads were 650 and 610 Kg/m^2 and live loads were 200 and 150 Kg/m^2 for floors and roof. Loading width of the frames was considered equal to 4 m. concentrated seismic masses were applied at the center of each floor, seismic masses consist of dead load plus 20% of live load (according to Iranian seismic code, Standard No. 2800). Design of these structures was performed by iteration. In each iteration the assumed structure was pushed by a load pattern proportional to product of first mode shape and story mass then the base shear capacity of structure V_{prob} and displacement capacity of structure U_{sc} (at effective height of structure) were calculated. After calculation of parameters defined in equations 1-8, the ratio defined in equation 9 was calculated. If this ratio was equal to 1 it represents %NBS equal to 100. The designed structures are shown in figure 2. Summary of calculations in the displacement based method are presented in tables 1 and 2 for 5 and 10 story structures respectively. Idealized pushover curve for calculation of structural ductility is shown in figure 3 for 10 story structure.

5. ACCELARATION TIME HISTORIES

Seven ground motions were selected from the strong ground motion database of the Pacific Earthquake Engineering Research (PEER) Center (http://peer.berkeley.edu). All the selected ground motions correspond to NEHRP (2003) soil class C. The 5%-damped spectrum of each scaled ground motion was constructed and the ground motions were scaled such that the average value of spectra does not fall below the 5%-damped spectrum of Iranian seismic code for soil type II in period range between 0.2T and 1.5T, where T is the fundamental period of the structure. The records were scaled to 0.61g for 5 story structure and 0.65g for 10 story structure. The detailed characteristics of the records used are given in table 3. Scaling of records for 5 story structure is illustrated in figure 4.

6. SEISMIC EVALUATION

In ASCE 41-06 both member-level (plastic rotation) limits and global-level interstory drift limits are provided to assess structural performance. While the member-level limits are intended for evaluation of structural components, the drift values given in ASCE 41-06 are typical values provided to illustrate the overall structural response. They are not provided as drift limit requirements, in this paper the 2.5 percent drift limit in ASCE 41-06 is only used as a guide to evaluate the overall structural response in life safety performance level and to investigate if 2.5 percent drift limit considered in displacement based method based on NZSEE recommendations have been satisfied or not. Interstory drift profiles for 5 and 10 story structures in all seven earthquakes are shown in figure 5, as shown in this figure interstory drifts in some of earthquakes have considerably exceeded 2.5 percent drift. The mean of interstory drifts in seven earthquakes for both structures have exceeded 2.5 percent drift in some stories. In five story structure mean of interstory drifts only in one story have exceeded 2.5 percent drift but in 10 story structure mean of interstory drifts in six stories have exceeded 2.5 percent drift, but in two stories this exceedance is very negligible.

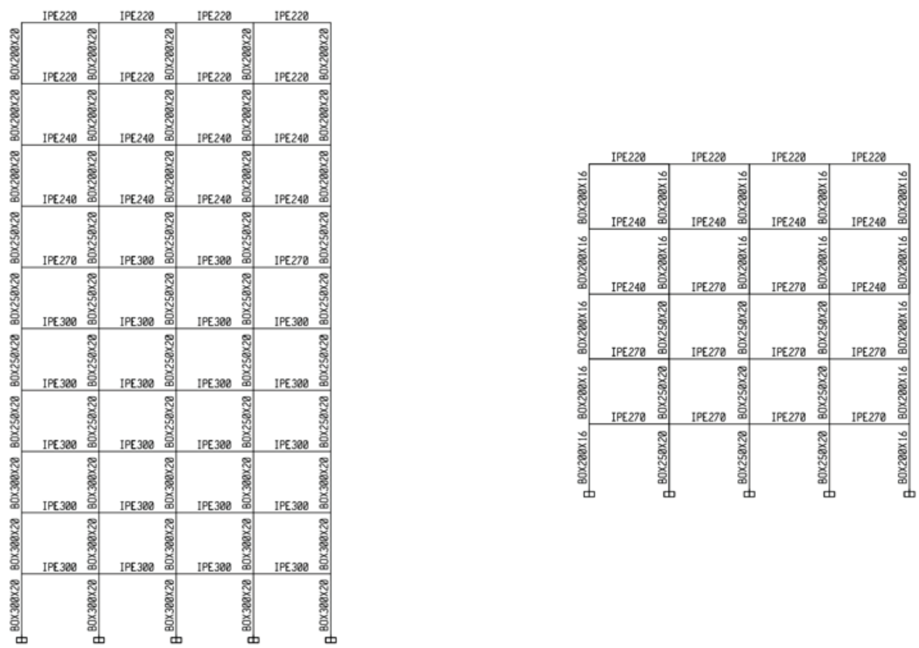

Figure 2: Designed structures

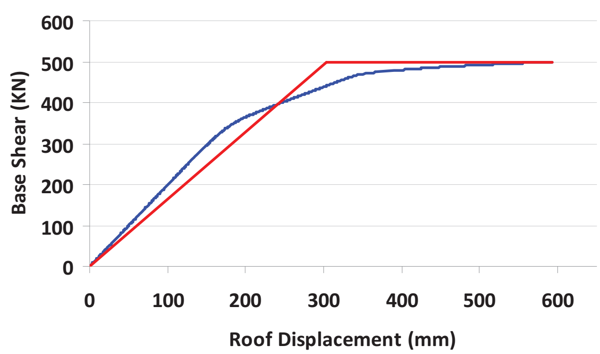

Figure 3: Base shear-roof displacement curve for 10 story structure

Table 1: Summary of calculations in the displacement based method for 5 story structure

Mass (kg)	Γ	T_{eff} (sec)	U_{sc} (mm)	μ	k_{eff} (N.m)
227955.4	1.340	2.099	224.179	1.583	2041850.529
ξ	S_p	K_ξ	$\delta(T_{eff})$ (mm)	U_{sd} (mm)	$U_{sc} / S_p U_{sd}$
0.1176	0.825	0.713	368.203	262.598	1.034

Table 2: Summary of calculations in the displacement based method for 10 story structure

Mass (kg)	Γ	T_{eff} (sec)	U_{sc} (mm)	μ	k_{eff} (N.m)
465922.5	1.406	3.936	421.002	1.956	1186912.625
ξ	S_p	K_ξ	$\delta(T_{eff})$ (mm)	U_{sd} (mm)	$U_{sc} / S_p U_{sd}$
0.1397	0.713	0.661	851.400	563.546	1.047

Table 3: Characteristics of selected ground motions

No	Earthquake name	Magnitude	Station name	Station	Component	PGA(g)
1	Loma Prieta	Ms (7.1)	Saratoga - Aloha Ave	58065	90	0.324
2	Cape Mendocino	Ms (7.1)	Eureka - Myrtle & West	89509	90	0.178
3	Imperial Valley	Ms (6.9)	Parachute Test Site	5051	225	0.111
4	Northridge	Ms (6.7)	Castaic-Old Ridge Route	24278	90	0.568
5	Landers	Ms (7.4)	North Palm Springs	5070	90	0.134
6	Kocaeli	Ms (7.8)	Mecidiyekoy	-----	0	0.054
7	Duzce	Ms (7.3)	Sakarya	-----	90	0.023

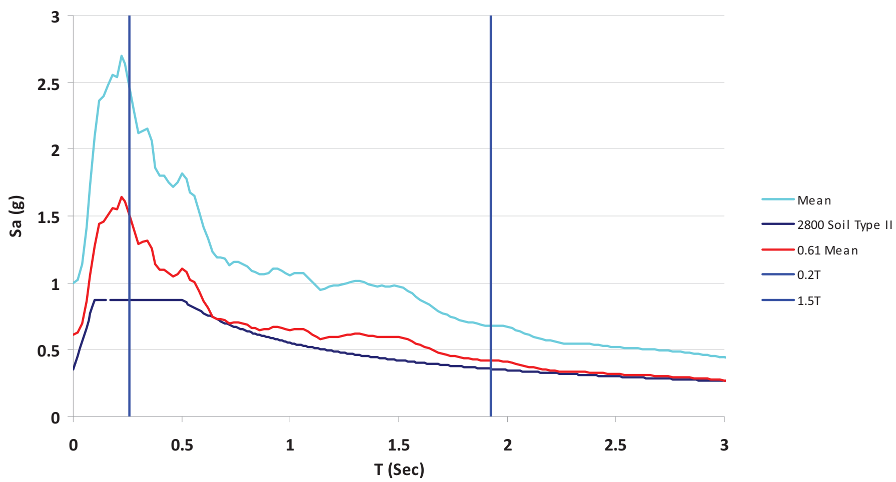

Figure 4: Scaling of motions to 0.61g for 5 story structure

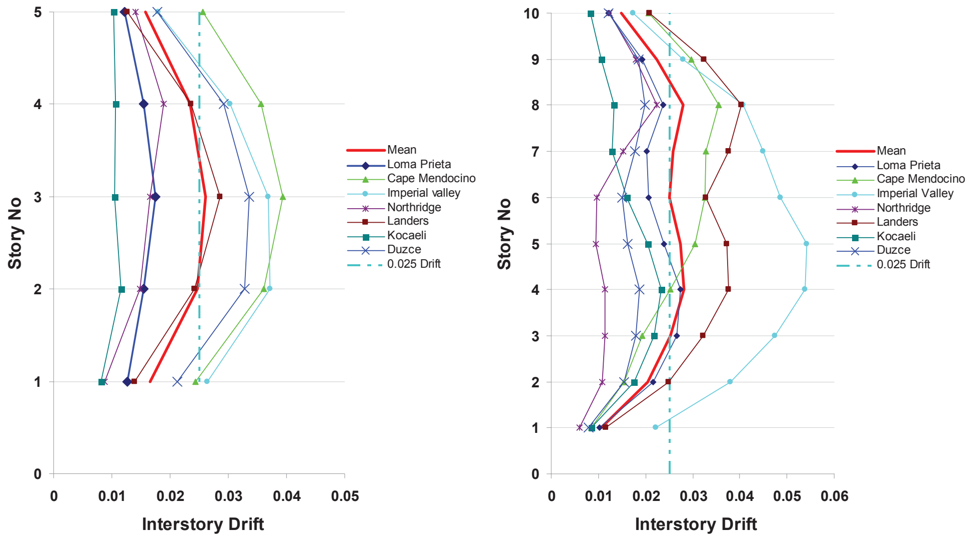

Figure 5: Interstory drift profiles for 5 and 10 story structures

Usage ratios are calculated by dividing element demand into capacity of the element for life safety, based on ASCE 41-06 acceptance criteria for primary members. In both of structures usage ratios for beams in some earthquakes have exceeded life safety acceptance criteria. Mean of usage ratios in seven earthquakes calculated by results of nonlinear dynamic analyses based on ASCE 41-06 life safety acceptance criteria are presented in figure 6. As shown in this figure the mean of usage ratios calculated by nonlinear dynamic analyses for all elements is lower than one, therefore these structures satisfy the life safety performance level for primary members in earthquakes with probability of exceedance equal to 10 percent in 50 years. As shown in figure 6 maximum of mean usage ratios in 10 story structure is more than maximum of mean usage ratios in 5 story structure.

7. CONCLUSIONS

In this paper two 5 and 10 story steel moment frame structures in Iran that satisfy %NBS equal to 100 based on displacement based method proposed in NZSEE recommendations are considered. Nonlinear dynamic analysis procedure is used to evaluate the performance of these structures. The results show that the mean of interstory drifts in nonlinear dynamic analyses have exceeded 2.5 percent drift that is considered in calculation of the displacement capacity U_{sc} of structures, especially in 10 story structure due to higher modes effects, but both of structures have satisfied the life safety performance level for primary members based on ASCE 41-06.

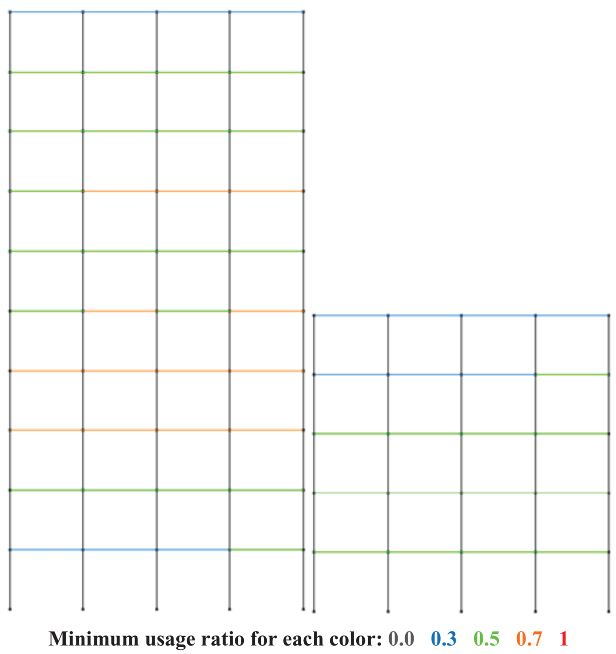

Figure 6: Mean of Usage ratios in seven earthquakes

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